Dependency of Building Fragility to source mechanisms of records selected for Incremental Dynamic Analysis

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ABSTRACT: Incremental Dynamic Analysis (IDA) is a computational procedure that allows a thorough assessment of seismic demand and capacity by using a series of non-linear dynamic analyses using suitably scaled earthquake records. An IDA curve for a particular earthquake record is developed by choosing a suitable engineering demand parameter (EDP) and intensity measure (IM), then scaling the record to a range of IM values, conducting non-linear dynamic analyses and plotting the IM vs. EDP curve. Previous research on IDA has used a suite of 'medium intensity' earthquake records scaled from 0.1- 2.0g PGA. In scaling the records, the acceleration amplitude is multiplied by the scaling factor. Hence, the duration and frequency content of the scaled records are unchanged. Nevertheless, using the medium suite of earthquake records does not account for the smaller time duration and higher frequency content observed in high intensity excitations. Hence, rather than using one set of records to represent all possible ranges of earthquake intensity, it is more logical to use different records which are more representative of the scaled intensity range. In this study, IDA of a multi-storey concrete building is conducted by using two different suites of ground motions recorded during earthquakes originating from (1) near source and (2) medium source mechanisms. Results show that using a single suite of medium source records can potentially lead to conservative predictions of behavior.

1 INTRODUCTION

The feasibility of Incremental Dynamic Analysis (IDA) as an appropriate method of seismic performance assessment has been researched extensively by Vamvatsikos and Cornell (2002). IDA is an analytical technique that allows accurate seismic demand and capacity prediction by using a series of nonlinear dynamic analyses under a scaled suite of earthquake records. Although IDA enables a thorough assessment of seismic demand and capacity, the process requires improvement to primarily enhance computational efficiency. The study presented in this paper however, examines the validity of the current method for performing IDA, whereby a single suite of ground motion records is used and scaled over a large intensity as opposed to using two or more suites of records to account for the changing characteristics of ground motion records that the scale factor does not capture.

2 IMPLEMENTATION OF IDA

To conduct IDA, first a computational model of the structure must be developed with appropriate material and geometric properties to encompass the full range of structural response from elastic behavior through to collapse. Secondly, a suite of earthquake records needs to be selected and all records should be scaled to several levels of Intensity Measure (IM). The structure is then subjected to each of the scaled earthquake records in the suite and a predetermined Engineering Demand Parameter (EDP) is monitored. These evaluations are carried out over a range of IM values to arrive at a matrix of data points on an IM vs EDP plot, representing the IDA curve. Many of the above steps can be automated using appropriate algorithms to select the scaling factors to apply to the records as well as running the computational simulations, therefore enabling the otherwise cumbersome process to be implemented without onerous time demands on users.

The selection of IM and EDP is by no means trivial and depends on the focus of the IDA. Current best practice suggests that for structures suitable to be modeled as a single degree of freedom (SDOF) system the 5% damped Spectral Acceleration (S_A) at the natural period of the structure is an appropriate IM (S_A=S_A[T, 5%]), as opposed to Peak Ground Acceleration (PGA). For multi-degree of freedom (MDOF) systems though, both PGA and S_A[T_1, 5%] (where T_1 is the period of the 1st mode response) have been used as the IM. When investigating the performance of the structure from a structural damage point of view, the maximum interstorey drift (θ_{max}) can be used as EDP as it relates well to joint rotations and both local and global collapse. On the other hand, when investigating non-structural damage, the horizontal floor accelerations would be more appropriate.

3 EARTHQUAKE RECORD PARAMETERS

Due to the erratic nature of earthquake records there are many parameters that can be used to describe their behavior. Typically the main parameters of interest are the ground motion intensity, time duration, and frequency. The intensity is a measure of the earthquake strength and typically PGA is used. The time duration is the period over which the earthquake occurs, and the frequency content of the record influences the participation of the different modes of the structural response.

As current IDA methods use only the IM to scale the records, there is no allowance for variations in time duration and frequency content. This is however, considered implicitly by using a suite of records as opposed to just a single record, and then employing a probabilistic framework to consider the dispersion and inherent uncertainty in structural responses to the suite of ground motions. Vamvatsikos and Cornell (2002) stated that although the scale factor is the simplest way to characterize the scaled images of the accelerogram, it is by no means ideal for engineering purposes as it offers no information on the energy content or true 'power' (referring to some of the aforementioned parameters) of the scaled record and its effect on the structure.

One qualitative parameter of an earthquake record not mentioned above that could be significant is the nature or 'source mechanism' of the earthquake record. It is well known that earthquake ground motions at short distances from an earthquake fault exhibit behaviour that is comprised primarily of one large acceleration peak and exhibits 'near-fault' or 'fling' effects. However, as the distance from the fault increases higher frequency components are filtered out and the amplitude also attenuates. Consequently, the record changes from being primarily comprised of one acceleration peak to containing multiple peaks of smaller acceleration amplitudes and an increase in effective time duration occurs. Two typical ground motion records are shown in Figure 1a and 1b for the medium intensity and high intensity suites respectively. Although the acceleration scales are different it can be seen that, (1) the high intensity ground motion is dominated by a peak acceleration at approximately 5 seconds, and although the record lasts for 30 seconds, the effective time period is approximately 15 seconds, (2) the medium intensity record has a longer time period and contains a more 'uniform' distribution of acceleration waves.

Source mechanisms of ground motion records can also be related to the intensity (PGA) of the record. For example, observed records with magnitudes around or exceeding the Maximum Considered Earthquake (MCE) level of 0.7g PGA occur, typically at short distances from earthquake faults. Therefore it would be expected that higher intensity ground motions would have a 'near-field' source mechanism. All of these features of earthquake records as a function of distance from the fault locations are well-known; however no allowance for this is made in current IDA analyses, where the same suite of earthquake records is scaled over the entire range of intensity measures from elastic response to collapse.

Current IDA allows scaling of a 'medium source' record to represent high intensity ground motions where in reality such high intensity earthquake records would have a 'near-field' source mechanism. If the displacement demand causes the structural response to become non-linear at the first major acceleration peak of the ground motion record then the stiffness will degrade and the vulnerability of the structure to sustain further damage from the remainder of the earthquake will increase. However, as 'near field' records are comprised primarily of only one large acceleration peak, then it is likely that the structure will not be subjected to the same displacement demands for the remainder of the earthquake

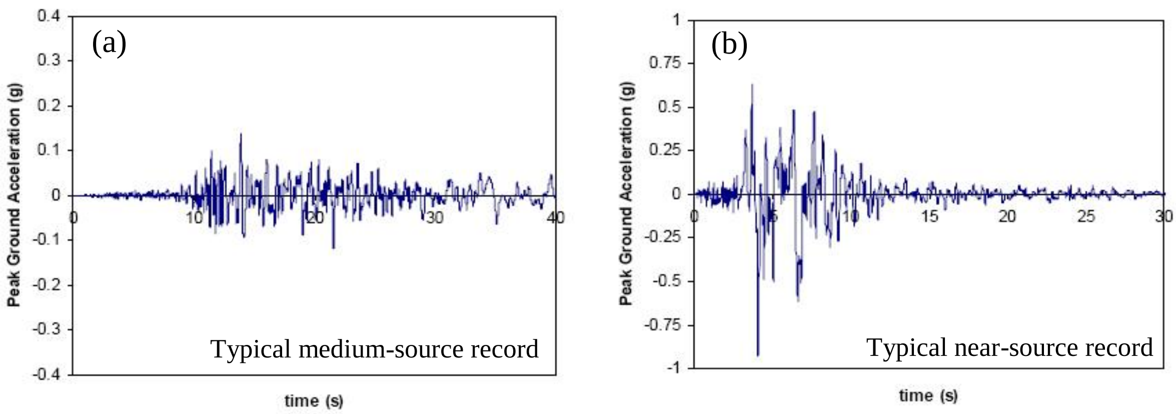

Figure 1: Comparison of earthquake ground motion source mechanisms

record. For the 'medium source' records however, there is likely to be further large displacement demands induced by high accelerations latter in the earthquake record. As the structural stiffness would reduce due to damage during the earlier acceleration peaks further damage (or collapse) is likely to occur during subsequent peaks. Hence, based on the above logic it would be expected that the structural demands due to a 'medium source' record scaled to a high IM will be more severe than when subjected to a 'near source' record scaled to the same IM.

4 CASE STUDY: DAD FRAME

To investigate the statement mentioned in the previous section, a computational model of a ten-storey moment resisting frame (Figure 2) designed based on Damage avoidance Design (DAD) principles was subjected to two suites of earthquake records, one 'near source' ground motion suite and the other 'medium source'.

4.1 *Computational model development and calibration*

Initially, an analytical model of a 3-dimensional beam-column joint subassembly was constructed using Ruaumoko3D (Carr, 2004). The beams and columns were represented using elastic Giberson beam frame elements. The behaviour of the rocking joint was described using two springs of zero length in parallel. The springs had tri-linear-elastic and elasto-plastic hysteretic behaviours representing the gap opening and supplemental damping system, respectively. No allowance for the yielding of the post-tensioning tendons was made. The parameters of the springs representing the rocking joints were calibrated based on preliminary quasi-static tests up to 3% drift on a rocking 3-dimensional beam-

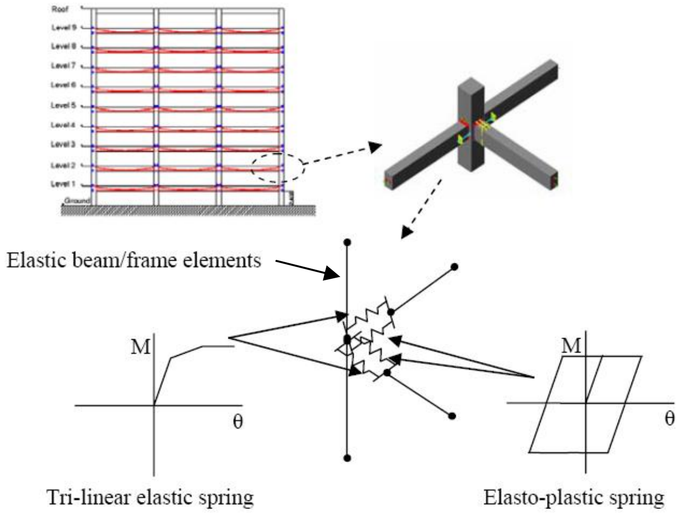

Figure 2: Computational model of building.

column subassembly designed for damage avoidance (Li, 2006). A full scale 3-dimensional model of the ten-storey prototype structure was then developed based on the adoption of parameters validated through experimentation. The prototype building contained damage-protected armoured rocking connections at beam-column joints on the first six stories, and rocking columns at the base in the ground floor and underneath the seventh floor. Connections from the seventh to the tenth floor were monolithic.

4.2 *Earthquake ground motion records*

Two suites of earthquake records described in Table 1 and obtained from the SAC steel project archive (SAC, 1995) were used to compare the response of the building to different ground motion source mechanisms. Ground motions 1-20 are the 'medium source' records and 21-40 the 'near source' records. The medium suite of ground motions had a median source distance of 16.9 km, magnitude of 6.7, and spectral acceleration of 0.171g, while the near source suite had median source distance, mag-

Table 1: Earthquake ground motion record properties

Ref	Event	Year	Station	M^{*1}	R^{*2} (km)	$S_A{}^{*3}$ (g)
1	Imperial Valley	1940	El Centro	6.9	10	0.136
2	Imperial Valley	1940	El Centro	6.9	10	0.041
3	Imperial Valley	1979	Array #05	6.5	4.1	0.210
4	Imperial Valley	1979	Array #05	6.5	4.1	0.180
5	Imperial Valley	1979	Array #06	6.5	1.2	0.172
6	Imperial Valley	1979	Array #06	6.5	1.2	0.210
7	Landers	1992	Barstow	7.3	36	0.180
8	Landers	1992	Barstow	7.3	36	0.093
9	Landers	1992	Yermo	7.3	25	0.074
10	Landers	1992	Yermo	7.3	25	0.470
11	Loma Prieta	1989	Gilroy	7	12	0.170
12	Loma Prieta	1989	Gilroy	7	12	0.160
13	Northridge	1994	Newhall	6.7	6.7	0.190
14	Northridge	1994	Newhall	6.7	6.7	0.097
15	Northridge	1994	Rinaldi	6.7	7.5	0.083
16	Northridge	1994	Rinaldi	6.7	7.5	0.110
17	Northridge	1994	Sylmar	6.7	6.4	0.280
18	Northridge	1994	Sylmar	6.7	6.4	0.021
19	North Palm Springs	1986	North Palm Springs	6	6.7	0.310
20	North Palm Springs	1986	North Palm Springs	6	6.7	0.210

Ref	Event	Year	Station	M^{*1}	R^{*3} (km)	$S_A{}^{*3}$ (g)
21	Kobe	1995	-	6.9	3.4	1.323
22	Kobe	1995	-	6.9	3.4	0.685
23	Loma Prieta	1989	-	7	3.5	0.550
24	Loma Prieta	1989	-	7	3.5	1.310
25	Northridge	1994	-	6.7	7.5	0.810
26	Northridge	1994	-	6.7	7.5	1.010
27	Northridge	1994	-	6.7	6.4	0.700
28	Northridge	1994	-	6.7	6.4	1.241
29	Tabas	1974	-	7.4	1.2	0.502
30	Tabas	1974	-	7.4	1.2	0.560
31	Elysian Park	-	Simulated	7.1	17.5	1.330
32	Elysian Park	-	Simulated	7.1	17.5	0.930
33	Elysian Park	-	Simulated	7.1	10.7	1.010
34	Elysian Park	-	Simulated	7.1	10.7	1.343
35	Elysian Park	-	Simulated	7.1	11.2	1.694
36	Elysian Park	-	Simulated	7.1	11.2	1.730
37	Palos Verdes	-	Simulated	7.1	1.5	0.850
38	Palos Verdes	-	Simulated	7.1	1.5	1.223
39	Palos Verdes	-	Simulated	7.1	1.5	0.690
40	Palos Verdes	-	Simulated	7.1	1.5	1.370

[1]Moment magnitude, [2]Epi-central distance, [3]Spectral acceleration at $T=T_1$

nitude, and spectral acceleration of 3.5 km, 7.1, and 1.01g respectively. Each of the records represents one of the two horizontal components of the earthquake records recorded in fault-normal and fault-parallel components. The components were then combined, rotated by 45 degrees, and resolved into orthogonal components. This allows the records to be used for both bi-directional and uni-directional computation.

A spectral analysis was carried out for the two ground motion records. Figure 3a shows the spectral acceleration of the two suites of records when scaled to a spectral acceleration of 1.0g at the fundamental time period of the structure, which was 1.6 seconds. It can be seen that when scaled to $S_A(T_1)=1.0g$ that the spectral acceleration for the medium suite is higher than the 'near source' suite, for both $T>T_1$ and $T<T_1$, as well as for both the 50th and 90th percentile curves. It can therefore be predicted that when conducting IDA the response to the medium source suite will be more severe than for the near source suite.

Because the computational model is 3-dimensional, an additional question regarding the orientation of the ground motion records with respect to the primary axes of the building is posed. Each orthogonal pair of earthquake records were compared and the larger component was applied along the seismic frame direction, with the smaller component applied in the gravity direction. This orientation was chosen based on a separate investigation using 5 uni-directional earthquakes applied in (1) the seismic direction, (2) the gravity direction, and (3) at 45 degrees from the two principal directions. The response interstorey drifts were maximum when the earthquakes were applied in the seismic direction. The use of this simplified approach was thought to be acceptable as the focus of this study was not to investigate the effect of "directivity" in 3-D modelling.

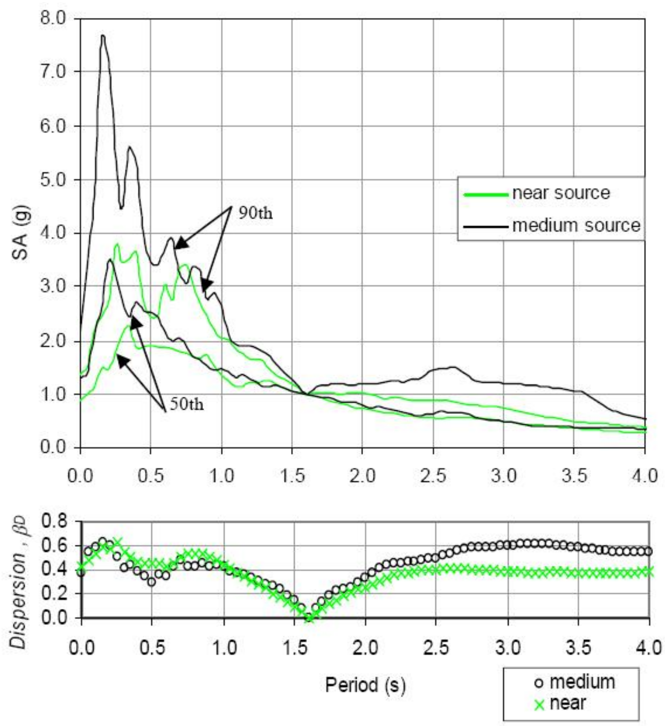

Figure 3a Spectral accelerations for each of the two suites of ground motions scaled to S_A=1.0g at T_1=1.6s.

4.3 *IDA results*

As the model was 3-dimensional two IDA plots were produced for each of the two orthogonal drift directions. A typical IDA plot for the near source suite for the maximum drift in the z axis direction is shown in Figure 3b. Each line in the figure represents the IDA plot (IM vs EDP) for an earthquake from the suite. A comparison in the response of the building to the two different suites of ground motions is presented in Figure 4 in the form of IDA percentile curves and the response dispersion for interstorey drift in the z direction. By sorting the ten EDP's at each IM, a survival probability can be defined by the following formula:

$$S_i = 1 - \frac{i - 0.5}{n} \qquad (1)$$

where i = the rank of EDP's (i.e. 10 to 1) in descending order and n = number of earthquake records. Each data point therefore has a failure probability associated with it, which allows the percentile curves in Figures 3b and 4 to be generated.

The individual data points and lines for each ground motion record have been omitted for clarity. It can be seen that as the intensity measure increases the 90th percentile response to the medium source suite of ground motions becomes more severe than that caused by the near source suite, but the 50th and 10th percentile response levels the response were similar. This was primarily due to the large re-

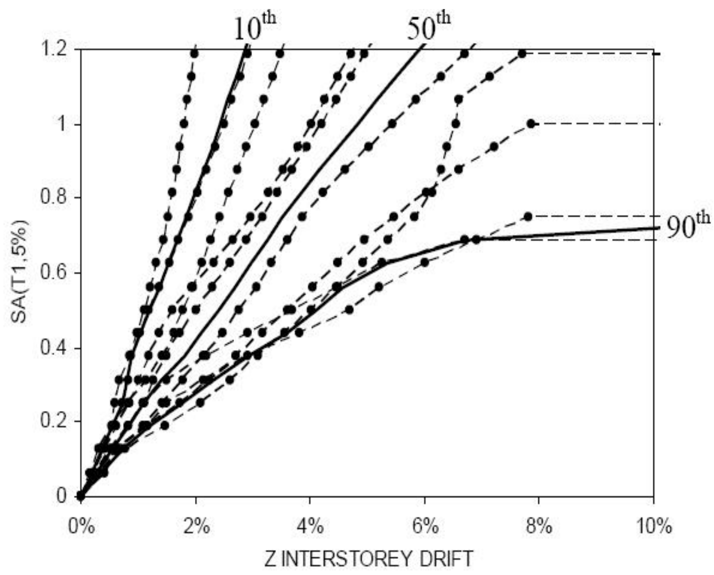

Figure 3b: IDA plot for the 'near source' ground motion suite.

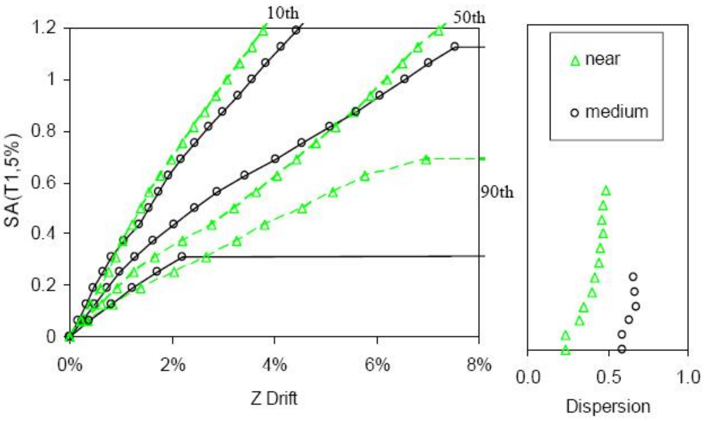

Figure 4: IDA percentile curves for the medium and near source ground motions

sponses generated by several of the medium source ground motions which caused a large 90th percentile curve but obviously had no effect on the other percentile curves.

One important parameter often overlooked in these analyses is that the results are used in a probabilistic framework and therefore both the median and the dispersion of the response are needed. A large dispersion quickly reduces the confidence in the analytical results and therefore should, where possible, be minimized. A smaller dispersion also means that less non-linear dynamic analyses are required to achieve the required level of confidence. The response dispersion as a function of spectral acceleration is also shown in Figure 4, where it can be seen that over the entire range of IM, the 'near source' ground motions give lower response dispersions than the 'medium source' motions.

5 FRAGILITY CURVES

Fragility curves can be used to estimate the likelihood during an earthquake event that user-defined Damage States (DS) are exceeded. The first step is to define the EDP boundaries at which each DS will occur. Table 2 presents the damage states used in this research, based on experimental tests conducted on a beam-column joint of the same prototype structure (Bradley et al., 2006).

Table 2: Damage state limits

	Damage State	Drift limit	Failure Mechanism	Repair required	Outage expected
DS1	None		Pre-yeild	None	None
		0.015			
DS2	Minor/ Slight		Dissipators yeild	replace dissipators	<1day
		0.045			
DS3	Moderate		Post-yeild, Spalling	Inspect, Re-tension	< 3 days
		0.1			
DS5	Complete		Collapse	Rebuild Structure	> 3 months

At each DS boundary the aforementioned principle is used to obtain percentile curves based on which survival probabilities are assigned to each of the ten sorted IM points for the corrosponding EDP. The resulting plot of fragility curves (Figure 5) show the probability of exceeding a certain damage state for a given IM.

Using the design acceleration spectra, the spectral acceleration can be related to the PGA by the following equation:

$$S_A = \frac{PGA}{T_1} \qquad (2)$$

where T_1 is the fundamental period of vibration, which for the ten storey building in this study is found to be T_1=1.6s. Hence, the spectral accelerations at the Design Basis Earthquake (DBE) (0.4g PGA) and Maximum Credible Earthquake (MCE) (0.72g PGA) are 0.25g and 0.45g, respectively.

Fragility curves for the medium suite of ground motions show that the probability of exceeding DS1 is 13% at the DBE intensity level and 75% at the

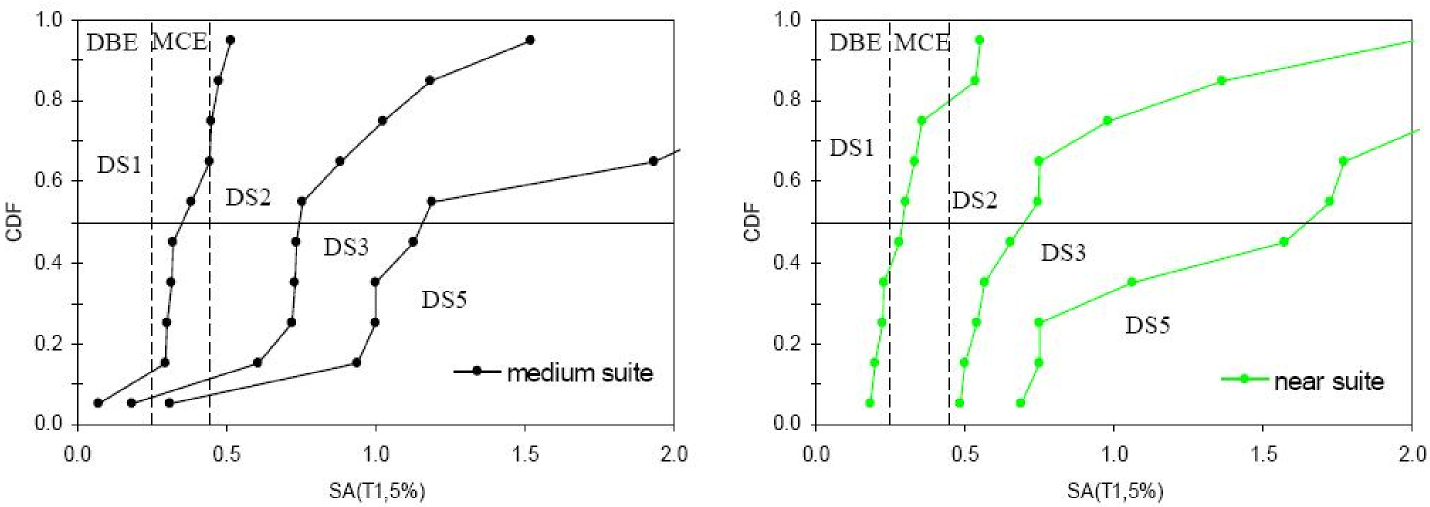

Figure 5: Fragility curve comparison for the two suites of ground motions.

MCE intensity level. On the other hand, using the near source suite increases the probability of exceeding DS1 to 39% and 50% at DBE and MCE intensity levels, respectively. Although the aforementioned increase in probability of DS1 due to near source suite than due to medium source suite is in contrary to earlier expectations, the comparison of the probabilities of the other two severer damage states DS3 and DS5 agree with the expectation that the medium source suite overestimates the response damage. The near source suite scaled to MCE and DBE intensity levels have almost zero probability of inducing these two severe damage states; whereas these probabilities for the medium source suite are 7% and 5% at DBE and 11% and 7% at MCE.

6 DISCUSSION

This research investigated the seismic response of a 3-dimensional ten-storey moment resisting concrete frame designed for damage avoidance when subjected to earthquakes from different source mechanisms. Two suites of records representative of 'near' and 'medium' source ground motions were applied to the structure and the severity of the response was measured in terms of maximum interstorey drift. Incremental Dynamic Analysis (IDA) was used to probabilistically analyze and compare the response of the structure to the two suites of records at high intensity measures. Using the experiment based damage state classification, fragility curves for the building were obtained from the IDA curves of the two suites.

From the results of the IDA, it can be seen that using a single suite of 'medium' source ground motions to represent the entire range of IM leads to a conservative prediction of structural response and an increased dispersion of results. It could be possible to define critical IM's below which the 'medium' source records can be used and above which 'near' source records should be used. The discontinuities between results over this 'transition' region could be addressed by using a weighted average of the two suites. The question is however, whether the extra effort to use multiple suites of records is worth the benefit gained. The answer to this problem has no trivial solution and should be considered on a case-by-case basis. However, if IDA was used to decide the earthquake records for a multi-level performance assessment philosophy (Dhakal et al., 2006), then using a single suite of 'medium' source ground motions may lead to the conclusion that the structure may not meet the third performance level, which is to be 90% confident that structural collapse will be avoided.

A comparison between the responses to the different suites in terms of fragility curves showed that at the DBE intensity level, the probability of the damage to the near source suite exceeding DS1 was higher than for the medium source suite, but the probability of exceeding the severer damage states was smaller. The response to the medium source suite at the MCE intensity level was far more severe with a 75% probability of exceeding DS1 and a 7% probability of collapse, as opposed to a 80% probability of exceeding DS1 and zero probability of exceeding DS2 and DS3 for the near source suite. It is again noted that for intensity levels such as MCE the near source suite represents true ground motion records as opposed to the scaled medium source records. Therefore, it can be justified from the above results that the procedure of scaling ground motion records over all scales of intensity level leads to conservative predictions of response.

7 CONCLUSIONS

Based on the research conducted in this study the following conclusions can be made:

1. A lower dispersion of structural responses to the 'near source' ground motions was observed compared to the responses to the 'medium source' suite. It indicates that a higher confidence can be put in the results obtained by near source records.
2. Fragility curves indicated that structural collapse at high intensity levels was probable using medium source records, however when using more representative near source records even moderate damage classified as DS2 was highly unlikely. Obviously, the use of medium source records overestimates the response and damage at high intensity levels.

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